

Submitted to ASHRAE-DOE-BTECC Conference on Building Thermal Envelopes

Simplified Modeling for Infiltration and Radon Entry

Max Sherman
Lawrence Berkeley Laboratory
Energy and Environment Division
Indoor Environment
Energy Performance of Buildings
Berkeley, CA 94720

Air leakage in the envelopes of residential buildings is the primary mechanism for provided ventilation to those buildings. For radon the same mechanisms that drive the ventilation, drive the radon entry. This paper attempts to provide a simplified physical model that can be used to understand the interactions between the building leakage distribution, the forces that drive infiltration and ventilation, and indoor radon concentrations. Combining both ventilation and entry modeling together allows an estimation of Radon concentration and exposure to be made and demonstrates how changes in the envelope or ventilation system would affect it. This paper will develop simplified modeling approaches for estimating both ventilation rate and radon entry rate based on the air tightness of the envelope and the driving forces. These approaches will use conventional leakage values (i.e. effective leakage area) to quantify the air tightness and include natural and mechanical driving forces. This paper will introduce a simplified parameter, the Radon Leakage Area, that quantifies the resistance to radon entry. To be practical for dwellings, modeling of the occupant exposures to indoor pollutants must be simple to use and not require unreasonable input data. This paper presents the derivation of the simplified physical model, and applies that model to representative situations to explore the tendencies to be expected under different circumstances.

NOMENCLATURE

A	Floor area [m^2]
C_∞	Undepleted soil radon concentration [Bq/m^3]
C_r	Radon concentration in the conditioned space [Bq/m^3]
C_w	Differential Wind Pressure Coefficient [-]
C_{in}	Internal Pressure Coefficient [-]
ELA	Effective leakage area [m^2]
RLA	Radon leakage area [m^2]
f_X	Leakage Asymmetry factor [-]
g	Acceleration of gravity [9.8 m/s^2]
H	Box height [m]
H_b	Depth of the basement floor below grade [m]
n	Leakage exponent [-]
P	(Air) pressure [Pa]
P_o	Reference Pressure [4 Pa]
ΔP	Representative pressure drop [Pa]
R	Box Parameter [-]
Q	Gas flow [m^3/s]
S_r	Radon entry rate [Bq/s]
v_o	Reference velocity [2.58 m/s]
X	Leakage asymmetry[-]
β_s	Neutral level [-]
ρ	Density (of air) [kg/m^3]

Subscripts indicate values associated with:

b	basement
e	entry
f	fan
o	reference
r	radon
s	stack
w	wind

INTRODUCTION

Groups attempting to develop standardized new-construction and mitigation practices to avoid elevated indoor radon concentrations have consistently come up against the problem of understanding the interaction between ventilation practices and indoor radon concentrations. To predict the concentration of radon in a house or other single-zone building it is necessary to know both the radon entry rate and the radon removal rate. Although radon can enter into homes by several mechanisms, the dominant radon entry path into homes with elevated radon concentrations is advective transport of soil-gas into the building (e.g. Nazaroff and Nero 1988), and the model developed is limited to radon entry by that pathway. Similarly, the only significant removal mechanism for radon once it is in the home is ventilation, and is the only one considered in the model. Because both the entry and removal mechanisms are dominated by pressure driven flow, it is important to model both the entry and removal simultaneously.

There are three basic means by which buildings are ventilated, mechanical ventilation by exhaust and/or supply fans, natural infiltration due to the wind, and natural infiltration due to the stack effect (i.e., buoyancy differences between indoor and outdoor air). As each of these ventilation mechanisms affects indoor pressure, they simultaneously affect radon entry rates as well as each other.

An exact solution to the problem of radon entry and ventilation requires a precise determination of all of the factors affecting them. Such a calculation is rarely possible for real buildings and even when it is, it sheds little light on the ramifications to the building stock. The approach taken in this report is to simplify the treatment of the house and soil system to maintain the underlying physical relationships, but eliminate the obscuring detail.

The focus of this report is the building envelope and the forces that drive ventilation and radon entry through it. Specifically, we will focus on pressure and leakage characteristics within the envelope. To do so we will necessarily ignore soil properties such as inhomogeneities, specific geometries, and any sub-soil interventions (e.g. sub-slab depressurization systems). This approach allows us to uncover the parameters that are critical for a general understanding of how the building interacts with the radon-bearing soil to yield steady-state radon concentrations.

BACKGROUND

Both ventilation and radon are areas of active study.* The key building shell parameter for quantifying infiltration is the envelope leakage. The total leakage of the exposed envelope can be measured by fan pressurization (ASTM E779, 1987) and can be expressed by a leakage area, ELA , and an exponent, n . (See, for example, Sherman (1990a).) In this form the flow of air at a specific applied pressure can be related to these parameters as follows:

$$Q = ELA v_o \left[\frac{\Delta P}{P_o} \right]^n \quad (1)$$

where ΔP is the applied pressure resulting in an airflow of Q . and v_o is the velocity related to the reference pressure, P_o :

$$v_o \equiv \sqrt{\frac{2P_o}{\rho_o}} \quad (2)$$

There also exists a large literature on detailed modeling of radon entry via soil-gas into buildings (Loureiro 1987, Revzan and Fisk 1990, Revzan et. al. 1991, Revzan et. al. 1991a), however a detailed model of radon entry is too complex to be appropriate for the simplified model being developed.

The radon entry rate is the product of the flow rate of soil gas entering the house, Q_e , and the concentration of radon in that gas, C_e . This concentration depends on the radon generation rate, and for higher flowrates, on the flowrate through the soil (Nazaroff 1988, Nazaroff and Sextro 1989). In general, above some critical pressure (i.e., flowrate), which depends on the geometrical configuration and the soil conditions, the concentration of the entering soil gas tends to decrease with increasing pressure. Under most situations encountered in the field, this *depletion* will not be an important factor. Therefore, for the purposes of this report we shall assume that no depletion takes place.

* To get a general overview for the topic of infiltration modeling see Chapter 23 of the *Handbook of Fundamentals* (ASHRAE 1989) and the summary by the Air Infiltration and Ventilation Centre (Liddament 1983).

SIMPLIFIED MODELING APPROACH

Two of the major assumptions associated with simplified modeling approaches are: to treat the the building as a single well-mixed zone; and to use a steady-state analysis. Both of these assumptions can break down in buildings. For example, houses with partially conditioned basements or zoned heating systems may not be well mixed. Similarly, soil response to unsteady driving pressures is not well studied. Nevertheless, these two assumptions shall be made in this report.

In this report we will also ignore the impact of inhomogeneities in soil properties. That is, we will assume that the only impact the soil has is as a reservoir of radon (at concentration C_∞) and as a flow resistance. We will ignore such effects as stack or wind effects in the soil due to the presence of the house.

We consider the house to be a well-mixed, single-zone, rectangular box falling into one of three types: crawlspace, slab-on-grade, and basement. The house is of height, H , above its zero. As this height represents the vertical distance of exposed leakage, the zero is defined as the floor level for crawlspace and slab houses, and grade level for basement houses.

The total leakage is assumed to be distributed around the exposed parts without significant concentration at any one location. The *box parameter*, R , is defined as the fraction of the leakage at the top ($h=H$) and bottom ($h=0$) of the box.

$$R \equiv \frac{ELA_H + ELA_0}{ELA} \quad (3)$$

thus $R=0$ would indicate that all of the house leakage was uniformly distributed in the walls and $R=1$ would indicate that all of the leakage was at the top and bottom of the box.

In general for any of the driving forces taken separately, the ventilation will be proportional to the following quantity:

$$\frac{ELA}{2} v_o f_X \left[\frac{\Delta P}{2P_o} \right]^n \quad (4)$$

where the proportionality constant often involves leakage distribution factors (e.g. the box parameter) and is related to the driving force, ΔP ; the leakage factor, f_X , varies between zero (for very asymmetric leakage distribution) and unity (for evenly distri-

buted leakage):

$$f_X \equiv (1-X^2) \left[\frac{2}{(1-X)^{1/n} + (1+X)^{1/n}} \right]^n \quad (5)$$

The leakage asymmetry is the fractional difference in leakage area between those areas under exfiltration and infiltration:

$$X \equiv \frac{ELA_{exfiltration} - ELA_{infiltration}}{ELA} \quad (6)$$

Since X is normally close to zero, f_X is normally quite close to unity.

Radon Entry

Radon entry will be determined by the pressure difference and resistance to flow at the radon entry site. In this report we assume that entry site is at a single height: for crawlspace and slab houses this height is at the floor; for basement houses this height is below grade (presumably at the basement floor level).

In most cases of soil flow the resistance of the soil is much larger than the resistance of the entry leak. Since flow through soil is generally linear in pressure we will assume that for slab and basement houses the entry exponent is unity. In crawlspace houses the entry leak is the floor itself and, we will, therefore, assume that the exponent for the entry is the same as the envelope.

To summarize we assume the following:

Table 1: RADON ENTRY PROPERTIES		
<i>HOUSE TYPE</i>	<i>ENTRY HEIGHT</i> H_r	<i>ENTRY EXPONENT</i> n_r
CRAWLSPACE	0	n
SLAB	0	1
BASEMENT	$-H_b$	1

We need a parameter to quantify the resistance of the leakage path from deep in the soil into the house. We can define a *Radon Leakage Area* (RLA) for radon entry

analogously to the *Effective Leakage Area* used for building envelope air leakage:

$$Q_{radon} = C_{\infty} RLA v_o \left[\frac{\Delta P}{P_o} \right]^{n_r} \quad (7)$$

where ΔP represents the pressure driving the entry.

RLA combines into a single parameter all of the information about the flow resistance of air entering the building through the radon-entry leaks. Like the *ELA* for the entire envelope its value is reduced from the open area of the leak face by the path length and aspect ratio of the flow path (i.e. the discharge coefficient is decreased from unity). Additionally, its value is further decreased by the flow resistance of the soil paths from the leak to the atmosphere. In most basements, for example, it is this soil resistance that dominates. *RLA* thus quantifies the radon resistance of the envelope.

Although no such test yet exists, it is conceivable that a pressure test to determine these parameters could be done in analogy to ASTM E779. For soil-contact situations it would difficult to estimate the parameters any other way. For crawlspace houses the *RLA* can be estimated from the floor leakage and the crawlspace radon concentration.

$$RLA = \frac{C_{crawl}}{C_{\infty}} ELA_0 \quad (8)$$

The crawlspace concentration can either be measured or estimated from the diffusive radon entry rate and the crawlspace ventilation.

STACK EFFECT

Both wind and stack effects are important for determining infiltration, but from a radon perspective, the most important of the natural driving forces is the winter stack effect.

A general derivation of stack-dominated infiltration can be taken from Sherman (1991), but under our simplifying assumptions, the stack-dominated ventilation rate of the building can be expressed as:

$$Q_s = \frac{ELA}{2} v_o \frac{1+nR}{1+n} f_{X_s} \left[\frac{\Delta \rho g H}{2P_o} \right]^n \quad (9)$$

where the leakage asymmetry is as follows:

$$X_s = \frac{ELA_H - ELA_0}{ELA} \quad (10)$$

A commonly quoted parameter is the neutral level, which is the height above zero at which there is no (stack-induced) pressure, divided by H . The neutral level is directly related to the (stack) leakage asymmetry:

$$\beta_s = \frac{1}{1 + \left[\frac{1-X_s}{1+X_s} \right]^{1/n}} \quad (11)$$

The entry of radon is determined by the pressure at the height of entry. Since we are limiting ourselves to winter conditions the entry leak will always be depressurized and there will be a continuous flow of radon-baring soil gas:

$$S_r = C_\infty RLA v_o \left[\left(\beta_s - \frac{H_r}{H} \right) \frac{\Delta p g H}{P_o} \right]^{n_r} \quad (12)$$

The steady-state concentration of the radon will be given by the ratio of the radon entry, S_r , to the ventilation, Q_s :

$$C_r = 2 C_\infty \frac{RLA}{ELA} \frac{1+n}{1+nR} \frac{(2(\beta_s - \frac{H_r}{H}))^{n_r}}{f_{X_s}} \left[\frac{\Delta p g H}{2 P_o} \right]^{n_r-n} \quad (13)$$

WIND EFFECT

Wind-induced ventilation has about the same importance as stack-induced ventilation for most climates, unless the buildings are highly sheltered. To derive an expression for this ventilation, we assume that the wind only drives infiltration through the walls (i.e. the floor and ceiling are shielded from the wind effects). (A derivation similar to the one above and is contained in Sherman (1990).) We are treating the wind speed as the *local* wind speed, fully corrected for any terrain and surroundings factors; thus the pressure coefficients correspond to an exposed structure:

$$Q_w = \frac{ELA}{2} v_o (1-R) f_{X_w} \left[C_w \frac{\rho v^2}{2 P_o} \right]^n \quad (14)$$

The leakage asymmetry (f_{X_w}), the equivalent pressure coefficient, (C_w), and the internal pressure shift, (C_{in}), will all be functions of wind angle and sheltering. The

leakage asymmetry will usually be positive,

$$0 < X_w < 0.5(1-R) \quad (15)$$

with the upper limit corresponding to wind striking a face head on, and the lower limit corresponding to wind striking a corner.

Both the equivalent and internal pressure coefficients are the result of the interaction between the leakage and pressure coefficients of each surface. C_{in} can be thought of as the leakage weighted average of the surface pressure coefficients and C_w is the deviation of the surface pressures from that average.

For unsheltered surroundings we can use the data from Allen (1984) to estimate the values of surface pressure coefficients. If we assume that the leakage distribution is not correlated with wind direction, C_w and C_{in} should fall in these corresponding ranges:

$$0.4 < C_w < 0.8 \quad (16.1)$$

and

$$0 > C_{in} > -0.2 \quad (16.2)$$

Values significantly outside these ranges are possible if the leakage distribution is highly asymmetric and correlated with wind direction. An example of such a case would be if the wind were striking a face of the structure that contained the majority of the leakage. In such a *wind trap*, C_{in} would be positive and C_w would be closer to zero. We will not consider such cases, herein.

Since in our model, radon entry can only be driven by changes in internal pressure, this latter equation indicates that there will be times when the pressure due to the wind driving radon entry will be insignificant. The wind pressure in the soil or crawlspace will be in between the pressures on the faces of the building, in much the same way as the internal pressure is. In fact, for a crawlspace whose leakage distribution mirrors the house, the effect is exactly the same; this fact coupled with the fact the wind will dilute the radon in the crawlspace allows us to ignore wind-induced radon entry in such a crawlspace house. For slab and basement houses the effect may be less extreme.

To put an upper estimate on this wind-induced radon entry pressure will assume

that the two pressure coefficients scale:

$$C_{in} \approx .25 C_w \quad (17)$$

to yield

$$S_r = C_\infty RLA v_o \left[.25 C_w \frac{1/2 \rho v^2}{P_o} \right] \quad (18)$$

Thus the following expression gives a reasonable upper limit for wind-induced radon under our assumptions:

$$C_r = \frac{C_\infty}{2} \frac{RLA}{ELA} \frac{\left[C_w \frac{1/2 \rho v^2}{P_o} \right]^{1-n}}{(1-R)f_{X_w}} \quad (19)$$

EXHAUST FAN

The previous two sections have derived the ventilation and radon entry when either of the two natural driving forces dominate; we now turn to mechanical systems. Since neither balanced ventilation systems or supply ventilation systems induce radon entry, the only thing which need concern us is an exhaust fan or other exhaust device (e.g. chimney) that dominates the ventilation.

Since the exhaust system dominates, the pressure follows the pressurization law, eq 1. The radon entry created by that induced pressurization will be

$$S_r = C_\infty RLA v_o \left[\frac{Q_{exhaust}}{ELAv_o} \right]^{\frac{n_r}{n}} \quad (20)$$

$$C_r = C_\infty \frac{RLA}{ELA} \left[\frac{Q_{exhaust}}{ELAv_o} \right]^{\frac{n_r}{n} - 1} \quad (21)$$

COMPARISON OF INDIVIDUAL DRIVING FORCES

Each of the three driving forces is created by a different phenomena; each has a different functional form. But for each driving force, the pressure that drives the infiltration through the envelope and the pressure that drives the radon entry are closely related; Table 2 displays the size of these pressures:

Table 2: DRIVING PRESSURES		
	<i>Radon Entry</i>	<i>Ventilation</i>
Stack Effect	$\beta_s \Delta \rho g H$	$(\frac{1+nR}{2(1+n)})^{1/n} \Delta \rho g H$
Stack (Basement)	$\Delta \rho g (\beta_s H + H_b)$	$(\frac{1+nR}{2(1+n)})^{1/n} \Delta \rho g H$
Wind Effect	$.1 \rho v^2$	$(\frac{1-R}{2})^{1/n} C_w^{1/2} \rho v^2$
Wind (Crawlspace)	negligible	$(\frac{1-R}{2})^{1/n} C_w^{1/2} \rho v^2$
Exhaust	$(Q_f/ELAv_o)^{1/n}$	$(Q_f/ELAv_o)^{1/n}$

The ratio of the radon entry pressure to the pressure driving ventilation gives a good indication of how effective each of these driving forces is at creating indoor radon. Table 3 presents these *Radon Source Ratios* and evaluates them for representative conditions and gives an indication of the ranges which might be observed in real buildings:

Table 3: RADON SOURCE RATIOS			
	<i>Equation</i>	<i>Representative</i>	<i>Range</i>
Stack Effect (Crawlspace/Slab)	$\beta_s (\frac{2(1+n)}{1+nR})^{1/n}$	2	0→3
Stack Effect (Basement)	$(\beta_s + \frac{H_b}{H}) (\frac{2(1+n)}{1+nR})^{1/n}$	4	1→10
Wind Effect (Basement/Slab)	$\frac{.1}{C_w} (\frac{2}{1-R})^{1/n}$	1	0.3→5
Exhaust	1	1	1

These values indicate that the stack effect (especially in basement houses) is much more efficient than the others at inducing elevated radon concentrations.

If we examine the expressions for concentration, we note that there are three parts to each: 1) the leading factor, $C_{\infty}RLA/ELA$, which is the same for all; 2) a factor depending on leakage distribution, and 3) a factor depending on the driving pressure. This suggests that the steady-state radon concentration can be expressed by a single equation of the following form:

$$C_r = C_{\infty} \frac{RLA}{ELA} f_R f_P \quad (22)$$

where f_R is the leakage distribution factor and f_P is the pressure correction factor.

The leakage distribution factor quantifies the effect that envelope leakage has on radon entry. Table 4 summarizes the appropriate equations, representative values and a range of values that would cover most houses:

Table 4: LEAKAGE DISTRIBUTION FACTOR, f_R			
	<i>Equation</i>	<i>Representative</i>	<i>Range</i>
Stack Effect	$\frac{2}{f_{X_s}} \frac{1+n}{1+nR} (2\beta_s)^{n_r}$	2.5	1.5→5
Stack Effect (Basement)	$\frac{2}{f_{X_s}} \frac{1+n}{1+nR} \left[2(\beta_s + H_b/H) \right]^{n_r}$	7	2→14
Wind Effect *	$\frac{1}{2(1-R)f_{X_w}}$	0.5	0→1.5
Exhaust	1	1	1

If the radon entry exponent and the leakage exponent were the same the pressure correction factor would be unity and the steady-state concentration would be independent of the magnitude of the driving forces. But, because there may be a difference in the two exponents, there is a slight dependency on the driving forces. Table 5 summarizes the appropriate equations, typical values and a range of values that would cover most houses:

* Note that for crawlspace houses and for wind directions that do not directly strike a face, the wind effect is negligible.

Table 5: VARIATION WITH DRIVING PRESSURE, f_P			
	<i>Equation</i>	<i>Representative</i>	<i>Range</i>
Stack Effect	$\left[\frac{\Delta \rho g H}{2P_o} \right]^{n_r - n}$	0.7	0.5 \rightarrow 1
Wind Effect *	$\left[C_w \frac{\rho v^2}{2P_o} \right]^{n_r - n}$	1.3	0.75 \rightarrow 1.5
Exhaust	$\left[\frac{Q_f}{ELAv_o} \right]^{n_r/n - 1}$	1	0.7 \rightarrow 1.4

The representative values used to generate table 5 are taken from Grimsrud, Sherman and Sonderegger (1983) to be typical of instances when that driving force dominates.

The radon concentration from each driving force scales similarly with soil concentration and total envelope and entry leakage, but differently with leakage distribution and pressure. If we combine these two effects we can compare the induced radon concentrations, for conditions representative of normal housing. Table 6 displays the indoor radon concentration, normalized by the soil concentration and total leakages:

Table 6: RADON CONCENTRATION [$\frac{C_r}{C_{\infty RLA/ELA}}$]		
<i>Driving Force</i>	<i>Representative</i>	<i>Range</i>
Stack (Basement)	5	1 \rightarrow 14
Stack	2	1 \rightarrow 5
Exhaust	1	0.7 \rightarrow 1.4
Wind	0.5	0 \rightarrow 2

Thus we expect the highest concentrations during stack-dominated periods, and the lowest during wind-dominated periods.

COMBINING MULTIPLE DRIVING FORCES

The analysis above considers only the case when one (of the three) driving forces dominates; in practice we usually need to consider the situation in which more than one contributes.

In Sherman (1990) a simplified solution was found for finding the total ventilation, Q_{total} , when multiple driving forces are operating. A similar analysis might be performed for the radon entry; the ratio of these two would then yield a new steady-state concentration. But, since the average entry pressures are strictly additive (unlike the average pressures driving infiltration), a combinatorial rule based on such an addition can be developed:

$$C_r = \frac{C_{r,w}Q_w \pm C_{r,f}Q_f \pm C_{r,s}Q_s}{Q_{total}} \quad (23)$$

where the minus signs are to be used if the corresponding driving force tends to pressurize the space (i.e. supply fans or summer stack effect).

Since the steady-state coefficients have different sizes and the total infiltration is superposed non-linearly, it is possible for a combination of driving forces to either raise or lower the radon concentration, but no combination can be significantly more than if the (winter) stack effect were operating alone.

EXAMPLE

To demonstrate the usefulness of this simplified approach we will consider an example house. The house is two story plus a full basement, which is well connected to the first floor, but the house is relatively leaky with a high neutral level (0.61). The soil has a moderate level of Radon and there is some radon entry in the floor of the basement. The house is relatively exposed and the wind strikes one of the four walls directly. The numerical summary follows:

$$\begin{aligned}
 \text{House Volume} &= 750\text{m}^3 & C_\infty &= 150,000\text{Bq/m}^3 \\
 \text{ELA} &= 2000\text{cm}^2 (0.2\text{m}^2) & \text{RLA} &= .1\text{cm}^2 (10^{-5}\text{m}^2) \\
 n &= 2/3 & R &= 0.3 \\
 X_s &= 0.15 & X_w &= 0.4 \\
 H &= 6\text{m} & H_b &= 2\text{m}
 \end{aligned}$$

Note that the basement volume (and leakage) is included in these numbers.

We calculate the infiltration and steady-state radon concentration for two periods of the year in a heating climate: (peak) winter and (windy) spring:

Table 7: LEAKY HOUSE EXAMPLE						
	<i>Winter</i>			<i>Spring</i>		
	$\Delta T:v$	<i>ACH</i> [h ⁻¹]	<i>C_r</i> [Bq/m ³]	$\Delta T:v$	<i>ACH</i> [h ⁻¹]	<i>C_r</i> [Bq/m ³]
<i>Stack</i>	40[K]	.98	43	10[K]	.39	27
<i>Wind</i>	2[m/s]	.43	5	3[m/s]	.74	7
<i>TOTAL</i>		1.18	38		.91	17

This example has chosen two high infiltration periods, but a house of this leakage in a moderate climate would still average about twice the annual ventilation specified by ASHRAE Standard 62 (1989), which is 0.35 air changes per hour. The radon concentrations in this house may not be of immediate concern, but this house is leaky and does not meet ASHRAE Standard 119 (1988) for envelope tightness—indicating that it is not energy efficient.

Consider a second example in which the conditions are the same, except that the envelope leakage is reduced from 2000 cm² to 350 cm², reflecting tight constructions practices that would meet Standard 119 in all climates. Since such a tight house would not meet ventilation standards, we will consider the addition of .25 ACH of mechanical ventilation as either balanced, exhaust or supply ventilation. Table 8 presents the air change rate and indoor radon concentration that would exist for our example house under four different ventilation strategies:

Table 8: TIGHT HOUSE EXAMPLE				
<i>Mechanical Ventilation</i>	<i>Winter</i>		<i>Spring</i>	
	<i>ACH</i> [h ⁻¹]	<i>C_r</i> [Bq/m ³]	<i>ACH</i> [h ⁻¹]	<i>C_r</i> [Bg/m ³]
None	.21	216	.16	98
Balanced	.45	98	.41	38
Exhaust	.30	174	.25	95
Supply	.36	102	.37	20

This example serves to demonstrate the impact that envelope tightness and mechanical ventilation can have on energy, ventilation, and radon concentration. It demonstrates that exhaust ventilation has only a minor impact on radon concentrations and that supply ventilation is superior to the other two forms for energy-efficient control of radon.

DISCUSSION

The simplified modeling approach has yielded some general results, but at the cost of ignoring some of the details. In this section we shall explore some of the impacts that these details might have.

We have assumed that the interior can be treated as a single zone for both pressure and concentration purposes. The presence of internal partitions such as closed doors can violate this assumption. Such a violation would be especially important in basement houses if the basement does not communicate easily with the first floor. In the extreme case (i.e. a basement that is better connected to outside than the first floor), the house is more appropriately treated as a crawlspace house.

The interactions of an air distribution system with internal partitions can cause local areas of pressurization and depressurization (Modera et al. 1991). Under such conditions the assumptions also breakdown. If such multizone effects become important, this simplified analysis becomes questionable.

An air distribution system can also cause whole building pressurization or depressurization through duct leakage. If this leakage can be quantified, it can be treated in the context of our model as a supply or exhaust fan, respectively. Although our model assumed no flues, stacks or chimneys, they too can be treated as fans, if their flowrates can be quantified.

Flues and chimneys can be driven by both stack and wind effects. In fact, in real buildings the principal wind contribution may come from the flow it induces in such vents. Our estimates of the wind effect assumed that the pressure in the soil was not significantly affected by the wind. Most likely, however, there will be an effect on the soil pressure and this will tend to reduce the steady-state wind effect—especially in permeable soils. Our model shows a relatively small wind effect; it may, however, still be over-estimating the size.

Although the wind effect may quite small in steady-state, it may contribute significantly under non-steady conditions—a case we did not analyze. Nazaroff and Nero (1988) indicate that the time constant for a pressure pulse in soils is on the order of minutes to hours. Since the internal pressure equilibrates on the order of seconds (Sherman and Modera, 1988), dynamic wind effects could be considerable. In general, the dynamic behavior in soil is not a well-understood topic and needs further research.

In addition to the wind effect in the soil, the stack effect in the soil can affect the steady-state concentration. We have assumed that the soil gas is at the same temperature as the local environment. The presence of the house and the thermal mass of the soil make this a questionable assumption, but its impact is not likely to be significant. For slab or crawlspaces houses the stack effect in the soil will have almost no impact on the entry. For basement houses, however, there could be an impact. If, for example, the soil is between inside and outside temperatures, the effective value of H_b should be decreased, thus mitigating some of the extra radon driving pressure in basement houses; alternatively, cold soil in the summer months could augment radon entry. On a seasonal or annual basis these effects are not likely to be significant.

Depletion, the effect of soil gas having a concentration less than C_∞ , is another soil-related effect that we ignored. Depletion requires a relatively short transit time of air through the soil into the house; it is most likely to occur when the soil is highly permeable and the leak is near the soil/atmosphere interface and the flow rates are large. Depletion will have the effect of decreasing the steady-state concentration at larger flow rates. Although depletion is not often significant, it is conceptually

possible to incorporate it into the simplified modeling approach.

The assumptions about envelope and radon leakage distribution that simplified the derivation, may be too simple to adequately describe all of the features found in real buildings. Thus, it may not be practical to use, for example, our expression for wind-induced *ventilation*, on its own. Rather the model becomes more robust because much of the detail cancels in the estimation of steady-state radon concentrations.

CONCLUSIONS

From our formalism it is clear that the three most important quantities for determining steady-state radon concentrations are the radon level in the soil, C_∞ , the below-grade integrity of the envelope, RLA , and the above-grade integrity of the envelope, ELA . Although ELA can vary over an order of magnitude among houses, C_∞ and RLA can each vary by *several* orders of magnitude.

Since it is not usually possible to change the soil radon concentration, the key parameter for controlling radon in houses is the Radon Leakage Area. Furthermore, there are no obvious energy or other penalties associated with decreasing RLA . This is not a surprising result. Unfortunately, sealing leaks in a basement or slab substructure has not proven terribly successful, probably because the leaks are quite small (compared to the total envelope leakage) and perfect sealing is difficult to attain. (Sealing the crawlspace from the house, however, could be a practical option. Sub-slab systems are also an alternative for controlling radon, but are not, as yet, treated in this simplified formalism.)

The next most important factor relating to radon concentrations is to determine which of the driving forces is the dominant one. For a given infiltration rate, the (winter) stack effect is much more effective at inducing radon entry than is the wind effect; exhaust ventilation is in between. Thus the winter radon concentrations are expected to be the highest of the year.

The distribution of leakage around the exterior envelope is of secondary importance in determining the radon concentration. Unless the distribution is extreme (i.e. $|X| \rightarrow 1$), radon concentrations can be estimated using typical values for the leakage distribution.

Similarly the absolute magnitude of the driving forces is of secondary importance. In fact, if the radon entry exponent is the same as the envelope leakage exponent, the steady state radon concentration (for a single driving force) is independent of that force. In such a case the stack, wind, and fan-induced ventilation rates are only necessary for combining the effects.

The main conclusion to be drawn from the work presented in this paper is that tractable simplified models can be developed for understanding the interactions infiltration and ventilation, and radon entry. The model developed allows us to examine the indoor radon implications of the simultaneous impacts on radon entry and dilution of building construction and operation alternatives. The model suggests that when dilution and radon entry are both taken into account, the impacts of several alternatives, such as exhaust fans, may not be as large as previously thought.

On the other hand, the answers obtained with even this simplified model can be somewhat sensitive to the values of parameters for which data is in short supply, such as soil concentrations and the dynamics of radon entry. The most crucial lack, however, is in the quantification of the entry path (i.e. *RLA*). There exists a strong need to develop appropriate measurement techniques and to apply them in the field to determine typical values of this parameter and how it varies under different construction and soil conditions.

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This work was sponsored by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technology of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and also supported by the Environment Protection Agency.

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